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Stressors Present in a Disabled Submarine Scenario: Part 1. Identification of Environmental, Mental, and Physical Stressors

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In the event that a submarine becomes disabled underwater, submariners trapped aboard the disabled submarine (DISSUB) must survive until rescue assets arrive or until deteriorating conditions mandate an escape. During this onboard survival period, submariners must perform cognitively-demanding tasks that will affect their likelihood of survival all while experiencing a myriad of stressors (e.g., air contaminants, hopelessness, and pain/injury). The purpose of this report was to comprehensively identify and classify the potential stressors that could be present in a DISSUB scenario. To accomplish this, we reviewed DISSUB literature and conducted interviews with DISSUB subject matter experts. Identified stressors were categorized as environmental, mental, or physical in origin, and each stressor was individually discussed regarding its potential source(s) of origin. Where appropriate we discussed the stressor's likelihood of occurrence, and the degree of exposure that submariners may experience over the course of a DISSUB scenario. A second report will review the potential cognitive effects of each identified stressor.

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Abstract

Despite generally being safe, a submarine may experience an incident that prevents it from being able to resurface or causes it to sink without the ability to resurface. In such an event, submariners trapped aboard the disabled submarine (DISSUB) must survive until rescue assets arrive or until deteriorating conditions aboard the DISSUB mandate an escape. During this onboard survival period, submariners must perform cognitively-demanding tasks that will affect their likelihood of survival all while experiencing a myriad of stressors (e.g., air contaminants, hopelessness, and pain/injury). This report is the first of two which intend to identify the potential stressors that could be present in a DISSUB scenario, review the potential cognitive effects of these stressors, and consider how these cognitive effects could impair submariner operations during the onboard survival phase of a DISSUB scenario. The purpose of the current report (Part 1) was to comprehensively identify and classify the potential stressors that could be present in a DISSUB scenario. To accomplish this, we conducted an operational assessment including review of DISSUB literature and interviews with DISSUB subject matter experts. Identified stressors were categorized as environmental, mental, or physical in origin, and each stressor is individually discussed regarding its potential source(s) of origin. Where appropriate we discussed the stressor's likelihood of occurrence and the degree of exposure that submariners may experience over the course of a DISSUB scenario. In a second report (Part 2), we will review the potential cognitive effects of each identified stressor and how they may affect survival efforts and operations during the onboard survival portion of a DISSUB scenario.

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List of Acronyms and Symbols

%	Percent
>	Greater than
°	Degrees
AFT	Aftermost compartment on a USN nuclear submarine
ata	Atmosphere absolute
BAP	Buque Armada Peruana (Peruvian Navy Ship)
CDR	USN Commander
Cl	Chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
dBA	Decibel (A-weighted)
DISSUB	Disabled submarine
e.g.	For example
EAB	Emergency air breathing equipment
F	Fahrenheit
FiCO2	Fraction of inspired carbon dioxide
FiO_2	Fraction of inspired oxygen
ft	Feet
FWD	Forward compartment on a USN nuclear submarine
H_2	Hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
HCl	Hydrogen chloride
HCN	Hydrogen cyanide
HMCS	Senior Chief Hospital Corpsman
i.e.	In other words
K	Soviet K-class submarine
L/hr	Liters per hour
LiOH	Lithium hydroxide
mg/day	Milligrams per day
NAVSEA	Naval Sea Systems Command
NAVSUBSCOL	Naval Submarine School
NH_3	Ammonia
NO_2	Nitrogen dioxide
NSMRL	Naval Submarine Medical Research Laboratory
O_2	Oxygen
oz	Ounces
pg	Page
$PiCO_2$	Partial pressure of carbon dioxide
PiO_2	Partial pressure of inspired oxygen
ppm	Parts-per-million

Ret.	Retired
RN	Royal Navy
scf	Standard cubic foot
SEAL	Submarine Escape Action Levels
SEV	Surface equivalent value
SHT	Special hull treatment
SME	Subject matter expert
SO_2	Sulfur dioxide
SS	Submersible ship (non-nuclear)
SSN	Nuclear-powered attack submarine
SurgCDR	Surgeon Commander (Royal Navy)
SURVIVEX	Survival exercise
U.S.	United States
UMO	Undersea Medical Officer
USN	United States Navy
USS	United States ship

Introduction

Submarines play an essential role in modern nuclear armament due to their low detectability, range of operation, and quick mobility. At the time of writing, the United States Navy (USN) maintains 71 submarines with active commissioning (NVR, 2019). Fortunately, the USN has not experienced a submarine casualty since the loss of the USS Scorpion (SSN 589) in 1968, and submarines are generally considered safe. Nevertheless, an incident could occur that would sink a surfaced submarine or render a submerged submarine unable to resurface. Historical inciting events that have caused submarines to become disabled include flooding (e.g., USS Squalus, 1939), collision with another vessel (e.g., BAP Pacocha, 1988), snagging with underwater cables (e.g., AS-28, 2005), and fire/explosion (e.g., K-141 Kursk, 2000).

Thankfully, a review of 64 historical disabled submarine (DISSUB) events suggests that the majority of DISSUB scenarios (80%) are survivable through either surface abandonment, escape, or rescue (Whybourn, Fothergill, Quatroche, & Moss, 2019). In scenarios where surface abandonment is not possible, survivors of the inciting event must survive aboard the submerged DISSUB until either rescue personnel arrive (the preferred course of action) or escape becomes necessary due to worsening conditions. This period is referred to as the onboard survival phase and may last up to seven days (i.e., the maximum time expected for rescue personnel to arrive; NAVSEA, 2013c). During this time, submariners must perform demanding operational duties, such as reacting to emergencies, performing stay-time calculations, and making critical survival decisions.

Throughout the course of the onboard survival phase, submariners are likely to experience a myriad of stressors from the environment (e.g., buildup of toxic gases), mental conditions (e.g., emotional trauma from experiencing a life-or-death scenario), and/or changes to their physical state (e.g., fatigue). Exposure to these various stressors is likely to impair submariners' abilities to successfully execute their operational duties during the onboard survival phase of a DISSUB scenario. This report is the first of two which intend to identify the potential stressors that could be present in a DISSUB scenario, review the potential cognitive effects of these stressors, and consider how those cognitive effects could impair submariner operations during the onboard survival phase of a DISSUB scenario. The focus of the present report (Part 1) is to identify and classify the potential stressors that could be present during the onboard survival phase of a DISSUB scenario (i.e., after the inciting event but prior to survivors executing escape procedures or being rescued).

Identifying the Stressors that are Present during a Disabled Submarine Scenario

To identify potential stressors, we reviewed DISSUB operational documents, reviewed the scientific literature, and conducted interviews with DISSUB subject matter experts (SMEs).

Literature Review

Operational literature and policy documents related to DISSUB scenarios were reviewed, including the Review of Submarine Escape Action Levels for Selected Chemicals (2002), the Nuclear Powered Submarine Atmospheric Control Manual (S9510-AB-ATM-010; 2013), North Atlantic Treaty Organization (NATO) DISSUB policy documents, the Seven Day DISSUB Survivability Life Support Stores Requirements policy statement (2010), the ANNEX Q OPLAN 2137 policy statement, and the NAVSEA SSN 774 Class Guard Book Distressed Submarine Survival Guide FWD Escape Trunk (Lockout Trunk) procedures. Although there are separate DISSUB guard books for all current classes of USN submarines, the SSN 774 class guard book was selected for primary review as it is representative of the USN's newest fast-attack submarines that include the latest technological advances.[1]

Additional DISSUB-specific literature was compiled through searches of Naval Submarine Medical Research Laboratory (NSMRL) technical reports and Undersea Medical Officer (UMO) theses. Searches of NSMRL Technical Report Directory were conducted with the keywords "DISSUB," "disabled submarine," "distressed submarine," "escape," "rescue," "abandonment," "casualty," and "casualties."

These searches returned 54 NSMRL technical and special reports with titles containing any of those keywords. After initial review, 10 reports were rejected as being irrelevant to DISSUB scenarios based on the full title (e.g., "A diving casualty suggesting an episode of thoracic squeeze: A case report" Strauss & Wright, 1969). Three reports were omitted because they were classified. Another 25 reports were omitted because they focused on phases of a DISSUB scenario other than onboard survival, such as escape procedures or at-sea survival following escape (e.g., Hall & Summitt, 1970; Ryack & Walters, 1973). The remaining 16 NSMRL reports, all of which explicitly identify stressors that could occur during the onboard survival phase of a DISSUB scenario, are listed in Appendix A.

In the absence of a searchable database for UMO theses, 24 UMO theses were identified as being potentially-relevant to a DISSUB scenario based on recommendation from SMEs and reviewing a list of UMO theses from 2000-present. Thirteen reports were omitted due to a focus other than the onboard survival phase (e.g., "Buoyancy ascent training training at sea: A summary of three exercises;" Rehme, 1960). The remaining 11 UMO theses are listed in Appendix A.

The compiled literature (operational/policy documents, 16 NSMRL reports, and 11 UMO theses) was examined thoroughly to identify any stressors that may occur in a DISSUB scenario. For example, the NAVSEA SSN 774 Class guard book card 3B START TIME ESCAPE DATA provided an example of calculating partial pressure at depth and expressing the value as a Surface Equivalent Value (SEV). The card states, "50% flooding in a compartment doubles the pressure to 2 ata." Therefore, in this example, both flooding and an increase in compartment pressure are identified as potential stressors. A detailed list of the stressors identified from each source can be found in Appendices B-1 through B-9.

Subject Matter Experts

In addition to reviewing DISSUB-specific literature, three DISSUB SMEs were consulted.

HMCS (SS/FMF) Mark Jarvis has served in the USN for 25 years and has acted as a medical department representative and squadron representative for 16 years. He has served five extended deployments and successfully completed the Disabled Submarine Senior Survival Course offered at NAVSUBSCOL in 2015.

SurgCDR Lesley Whybourn, RN is an Occupational Medicine Physician with 25 years of service in the British Royal Navy. She has 28 years training and experience in the medical field with 22 years of experience in underwater medicine. In her current role as British Exchange Officer and Principal Investigator at NSMRL, SurgCDR Whybourn studies the application of prolonged field care to DISSUB scenarios.

[1] Due to similarities and redundancies between the 774 Class Guard Book Distressed Submarine Survival Guide FWD Escape Trunk (Lockout Trunk) and the 774 Class Guard Book Distressed Submarine Survival Guide AFT Escape Trunk (Lockout Trunk), this report focuses specifically on the FWD survival guide.

CDR Anthony Quatroche, USN (Ret.) served in the USN from 1978 to 2001. During that time he served seven extended deployments and served as Executive Officer of the USS Whale (SSN-638) from 1990 to1993. In his current role, CDR Quatroche is responsible for the maintenance and upkeep of the DISSUB guard books at NSMRL. He is also an author on this paper.

During the interview process, each SME was individually presented the list of stressors that were identified through the literature review. They were asked to identify any additional stressors that could occur during the onboard survival phase of a DISSUB scenario. A list of the stressors identified by each SME can be found in Appendix B-10.

Compiling Stressors

Based on the literature review and SME interview process, a comprehensive catalog of DISSUB stressors is listed in Table 1. At this stage, all potential stressors from each source were noted, even if they were redundant or encompassed stressors listed in other sources. For example, Eckenhoff (1980), Kargher, Ryder, Wray, Woolrich, and Horn (2001), and Alvis (1952) identify “air contaminants,” “toxic gases,” and “chlorine gas” as stressors, respectively. While these stressors are closely related, they are not synonymous; thus, they are each listed in Table 1.

Table 1

List of identified stressors present during a DISSUB scenario

Air contaminants	Increased compartment pressure
Ammonia gas	Increased humidity
Blunt trauma	Increased compartment temperature
Boredom	Increased nitrogen partial pressure
Buildup of sanitary waste	Increased oxygen partial pressure
Caffeine withdrawal	Insufficient training
Change in diet	Interpersonal conflict
Change in leadership	Isolation
Carbon monoxide gas	Lack of communication with rescue forces
Chlorine gas	Lack of control
Cold water exposure	Lack of potable water
Confinement	Life-or-death scenario
Dead bodies/dismemberments	Limited physical activity
Decreased compartment temperature	Lithium hydroxide dust
Decreased oxygen levels	Loss of confidence
Dehydration	Loss of power/minimal power
Drowning	Musculoskeletal trauma
Ear/sinus pain	Nitrogen dioxide gas
Electrical shock	Nitrogen narcosis
Exhaustion	Oxygen toxicity
Fatigue	Pain
Fear	Panic
Feeling of impending doom	Penetrating trauma
Flying glass	Personal injury
Fire	Poor hygiene

Flooding	Psychological stress
Food rationing	Pulmonary injury
Headaches	Radiation exposure
Heat exhaustion	Red emergency lighting
Heat stress	Reduced lighting
Heat stroke	Resignation
High-fat diet	Smoke inhalation
Hopelessness	Sulfur dioxide gas
Hunger	Tapping on the hull
Hydrogen chloride gas	Thermal injury
Hydrogen cyanide gas	Toxic gases
Hydrogen sulfide gas	Unhealthy atmosphere
Hyperthermia	Water rationing
Hypothermia	Water sprays
Hypoxia	Wet clothing/bedding
Increased carbon dioxide levels	Wounds
Increased carbon dioxide partial pressure	

Categorizing the Identified Stressors

Prior to categorization, the following steps were taken to reduce the stressors identified in Table 1: 1. Phenomenologically-similar stressors were combined; for example, change in diet, high-fat diet, and food rationing were all categorized under “nutrition.” 2. Terms that describe the physiological effect of a stressor rather than the stressor itself were removed; for example oxygen toxicity was removed because it is the effect of increased oxygen partial pressure. 3. Stressors that were overly general and encompassed other stressors on the list were removed; for example, the loss of power was removed because it is the origin of a multitude of other stressors (e.g., increased compartment temperature, increased carbon dioxide levels, reduced lighting, etc.).

The remaining stressors were then classified into three groups: <u>Environmental stressors</u> are those that originate in the surroundings of the DISSUB environment and include *atmospheric composition* (decreased oxygen levels, increased carbon dioxide levels, increased carbon dioxide partial pressure), *air contaminants* (ammonia gas, carbon monoxide gas, chlorine gas, hydrogen chloride gas, hydrogen cyanide gas, hydrogen sulfide gas, lithium hydroxide dust, nitrogen dioxide gas, sulfur dioxide gas), *lighting* (reduced lighting, red emergency lighting), *noise* (tapping on the hull), *fire* (smoke inhalation), *thermal* (cold water exposure, decreased compartment temperature, increased compartment temperature, increased humidity, wet clothing/bedding), *flooding* (drowning, water sprays), *increased compartment pressure* (increased oxygen partial pressure, increased nitrogen partial pressure), and *radiation*. <u>Mental stressors</u> are potential psychological states of mind or any stimuli that may result in a state of anxiety. These stressors are not tangible and include *boredom*, *confinement/isolation* (limited physical activity, lack of communication with rescue forces), *conflict among crew members* (change in leadership, interpersonal conflict), *hopelessness* (fear, feeling of impending doom, insufficient training, lack of control, loss of confidence, resignation), and *death of shipmates* (dead bodies/dismemberments). <u>Physical stressors</u> are those that stimulate a physical reaction of the body; physical stressors include *caffeine withdrawal, insufficient water intake* (lack of potable water, water rationing), *fatigue* (exhaustion), *poor hygiene* (buildup of sanitary waste), *nutrition* (change in diet, high-fat diet, food rationing), and *pain/injury* (blunt trauma, ear/sinus pain, electrical shock, flying glass, headaches, hunger, musculoskeletal trauma, penetrating trauma, personal injury, pulmonary injury, thermal injury, wounds). The categories of the identified stressors are summarized in Table 2.

Table 2
Categorization of identified stressors

Environmental Stressors	Mental Stressors	Physical Stressors
Thermal	Confinement/isolation	Pain/injury
Atmospheric composition	Death of shipmates	Nutrition
Air contaminants	Hopelessness	Insufficient water intake
Increased compartment pressure	Boredom	Caffeine withdrawal
Flooding	Conflict among crew members	Fatigue
Fire		Poor hygiene
Lighting		
Noise		
Radiation		

We acknowledge that many of the identified stressors are interrelated and may induce other stressors. For example, a fire will likely cause other environmental stressors, such as an increase in air contaminants and thermal stress; additionally, a fire may cause or exacerbate mental stressors (e.g., death of shipmates if any submariners are severely burned) and physical stressors (e.g., fatigue and dehydration among submariners combating the fire). The inter-relationships among stressors are highlighted throughout this review.

Origin and Occurrence of each Identified Stressor in a DISSUB Scenario

Environmental Stressors

Thermal. During normal submarine operations, heat is continuously generated by engines, storage batteries, galley facilities, electrical equipment, and human metabolic production. Due to the likely loss of power in a DISSUB scenario, most of these heat sources will be inactive, and the only remaining sources of heat will be from residual mechanical output, human metabolic production, the use of lithium hydroxide (LiOH) curtains to abate CO_2, and the burning of oxygen candles (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Fire(s) also may occur during a DISSUB scenario, either as the inciting event or a direct/indirect result of another event, and could produce large amounts of heat commensurate with the size of the fire. Because the occurrence of fire(s) is variable during a DISSUB scenario, their contribution to increased compartment temperature varies widely.

Due to the limited sources of heat (excluding fire) in a DISSUB, early mathematical models projected that compartment temperature would progressively decrease due to the rapid discharge of heat through the submarine's hull into the seawater. This rapid compartment heat loss was observed in several historical submarine casualties (*Submarine Casualties Booklet*, 1966); for example, the compartment temperature aboard the USS Squalus decreased to 36°F over two days (*Submarine Casualties Booklet*, 1966). Thus, until recently, it was a widely-accepted notion that compartment temperature would decrease during DISSUB events.

However, this presumption was challenged by data from two simulated DISSUB survival exercises (SURVIVEX) using modern submarines: SURVIVEX 2003 (USS Dallas) and 2004 (USS Salt Lake City). Model projections calculated prior to the exercises estimated that temperatures aboard the USS Dallas would decrease to 50° F within three days due to the cold weather conditions (average air temperature 41°F; average seawater temperature 37°F) (Horn et al., 2009). Contrary to this prediction, temperatures within the boats steadily rose over the course of both the exercises, eventually reaching an average of 80° F on the USS Dallas and 85°F on the USS Salt Lake City (see Horn et al., 2009 for a further discussion on boat temperatures across compartments). It was later deduced that the mathematical models failed because they did not account for the Special Hull Treatment (SHT) installation. SHT is a component of modern USN submarines designed to reduce the acoustic returns from active acoustic homing torpedoes (Mizokami, 2017, March 7); however, it also incidentally has high thermal insulating capabilities. Thus, the relatively minimal heat that is produced in a DISSUB from residual mechanical activity, metabolic production, LiOH curtains, oxygen candles, and potential fire(s) rapidly builds up within the boat. An increase in compartment temperature is now a widely-accepted consequence of a DISSUB event.

Operating procedures now mandate that efforts are made to mitigate the buildup of heat during a DISSUB scenario. The DISSUB guard book states that even if power is available, no cooking should be performed in order to limit heat generation (NAVSEA, 2013a). Similarly, survivors who are not performing essential duties (e.g., measuring air contaminant levels throughout the boat) are required to strictly limit their physical activity in order to reduce both metabolic O_2 demand, CO_2 production, and metabolic heat generation (NAVSEA, 2013b).

On an individual level, submariners may be able to take measures to mitigate the effects of heat buildup. For example, submariners can immerse body extremities in cool water and/or lean against cool metal surfaces like uninsulated hull areas to lower their body temperature (NAVSEA, 2013b). If possible, survivors can move to lower compartments of the boat, which are likely to be lower in temperature than upper compartments (Horn et al., 2009). Despite these efforts, increased compartment temperature may still affect submariners in a DISSUB scenario, and the guard book recommends the institution of a “buddy system” in which individuals will periodically monitor each other for symptoms of heat stress and intervene as needed (NAVSEA, 2013b).

Although the DISSUB guard book warns of the likely buildup of heat and cautions that it could affect survival efforts, no criteria are given for when rising temperatures are sufficient to require escape. Instead, it is left to the discretion of the senior survivor to initiate escape procedures if they deem that severe or worsening heat conditions will significantly jeopardize crew survival chances (NAVSEA, 2013b). Thus, while it is likely that heat buildup will occur as a stressor in most DISSUB scenarios, the exact degree will vary on a case-by-case basis. Future iterations of the DISSUB guard book should include standardized criteria regarding when heat buildup should initiate escape procedures (Ochsner, 2003).

Increases in humidity are also likely to occur and will exacerbate the effects of increased heat. Throughout a DISSUB event, the water content of the air will likely steadily increase due to survivor respiration, evaporation of sweat, and the reaction between LiOH and CO_2 (Berglund, Yokota, & Potter, 2013). During the SURVIVEX simulations, the average humidity aboard the USS Dallas peaked at 71% on the third day, with other compartments reaching 81% (Horn et al., 2009). Similarly, mean humidity aboard the USS Salt Lake City reached 85% by the fourth day, with other areas reaching humidity levels >90% (Horn et al., 2009).

The only scenario expected to result in decreased (instead of increased) temperature is significant flooding of the survivors' compartment(s). Flooding may occur on a DISSUB either as the inciting event or as a result of the inciting event (see Flooding section, pg. 13). Without any insulation from cold floodwaters, the ambient air temperature will rapidly decrease. This is one reason that the temperature aboard the flooded USS Squalus decreased to 36°F over the course of two days (*Submarine Casualties Booklet*, 1966). Direct contact with cold seawater (e.g., from spray leaks or immersion) can rapidly conduct body heat away from individuals. Continued contact with damp clothing or bedding will also draw heat away for hours after initial exposure. Despite these possibilities, decreased temperature is not as likely as an increase in temperature in a modern DISSUB scenario.

Atmospheric composition. The submarine atmosphere is unique from a natural environment in that it is nearly a fixed volume, and the air that is inside the boat when initially sealed is recycled and cleaned for up to months until the ship is able to ventilate (i.e., exchange the interior atmosphere with outside air). Ventilation can only be accomplished when the submarine is in a tactical situation that permits it to proceed to periscope depth and expose the larger snorkel induction mast — neither of which will be possible if the submarine is disabled. Additionally, the primary atmospheric control equipment will be shut down or disabled in a DISSUB scenario, leaving only limited atmosphere control capabilities. For these reasons, there is a potential for the atmospheric composition to rapidly change from safe to unhealthy in a DISSUB scenario due to changes in atmospheric composition or introduction of air contaminants.

***Decreased oxygen levels*.** During normal operations, the atmospheric concentration of oxygen (O_2) on a submarine is kept in the range of 18-21% surface equivalent value (SEV), with 21% SEV selected as the upper limit in order to reduce the risk of fires (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). While ventilation is generally the preferred means to manage atmospheric composition (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013), operational constraints, such as maintaining stealth, may preclude a submarine from being able to ascend to periscope depth. As this is often the case, submarines are equipped with low-pressure electrolyzer equipment used to continuously replenish O_2. During a DISSUB scenario, ventilation will not be possible, and the electrolyzer will likely lose power. Thus, the ability to replenish O_2 in the atmosphere will be limited, and O_2 levels are expected to gradually deplete (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). For example, during SURVIVEX 2003, O_2 levels fell from 21% to 17% SEV over 30 hours (Horn et al., 2009).

The preferred means of replenishing O_2 in a DISSUB scenario is burning chlorate candles. A single chlorate candle provides sufficient oxygen for a single survivor for up to 115 hours (NAVSEA, 2013c). However, burning chlorate candles also releases small amounts of carbon monoxide, chlorine, and additional heat into the submarine atmosphere, which must be further monitored (see Air contaminants section, pg. 9; *Nuclear Powered Submarine Atmosphere Control Manual*, 2013). As a last resort for replenishing O_2, bleeding the air banks can be used prior to donning emergency air breathing equipment (EABs; NAVSEA, 2013c). The EAB system provides full-face masks that allow survivors to breathe from the boat's high-pressure air banks (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). However, use of the air banks for this purpose is discouraged because it also leads to increasing compartment pressure (see Increased compartment pressure section, pg. 11; *Nuclear Powered Submarine Atmosphere Control Manual*, 2013).

Predicting the available amount of O_2 and its rate of depletion during a DISSUB scenario is challenging due to variability in conditions across DISSUB events. For example, fire events during a DISSUB can drastically deplete available O_2, with depletion rates commensurate with the size of the fire (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). The number of survivors will also affect O_2 depletion rate due to each individual's respiratory demand (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Individuals consume approximately one standard cubic foot (scf) of O_2 per hour under normal operating conditions; however, resting oxygen consumption rate can be 30% higher during a DISSUB scenario due to conditions such as cold-exposure or stress (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). O_2 consumption rate is also dependent on survivors' activity levels (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Individuals only consume approximately 0.5 scf per hour O_2 during sleep; conversely, individuals consume approximately 1.8 scf while performing machine maintenance and repair (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). As such, survivors who are not engaged in essential duties are required to strictly limit their physical activity (NAVSEA, 2013b) to reduce O_2 consumption.

Decreasing O_2 levels during a DISSUB is a limiting factor for survivors in a DISSUB scenario awaiting rescue (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). As such, the NAVSEA 774 class guard book (NAVSEA, 2013c) stipulates submariners must escape prior to O_2 levels reaching 16% SEV. The rate at which this level is reached will primarily depend upon the availability of chlorate candles, changes to the compartment pressure (see Increased compartment pressure section, pg. 11), and the number of survivors (NAVSEA, 2013c).

Increased carbon dioxide levels. During normal operations, the atmospheric concentration of carbon dioxide (CO_2) on a submarine is allowed to fluctuate from 0.03% to 4% SEV for up to 72 hours; however, CO_2 levels are most typically maintained $\leq$0.5% SEV (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Aside from ventilation of the boat, powered monoethanolamine CO_2 scrubbers are the primary means of reducing CO_2 levels during normal submarine operations. However, with the likely loss of power during a DISSUB scenario, this equipment will no longer function.

During a DISSUB scenario, the rise of CO_2 may be mitigated using non-regenerative lithium hydroxide (LiOH) methods. LiOH chemically breaks down CO_2 and is the only non-regenerative method on USN submarines for removing CO_2 from the atmosphere in a DISSUB scenario. Previous research has found that LiOH curtains are an effective method of maintaining CO_2 levels between 1.5% and 2.5% SEV (Horn et al., 2009; Norfleet & Horn, 2003). As such, submariners are instructed to deploy all LiOH curtains as soon as possible at the onset of a DISSUB scenario (Horn et al., 2009; *Nuclear Powered Submarine Atmosphere Control Manual*, 2013).

The rate of CO_2 generation and accumulation aboard a DISSUB varies widely based on the scenario. For example, significant quantities of CO_2 may be produced in the event of a fire (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). In the absence of fire, the number of survivors will be the primary factor affecting CO_2 production. On average, individuals produce CO_2 at a rate of 0.1 pound per hour or 0.8 to 0.85 scf per hour due to respiration and metabolic activity (Francis et al., 2002; Horn et al., 2009); however, this rate may vary, and the guard book implements various countermeasures to reduce individual contributions. To limit respiratory production of CO_2, survivors are required to limit physical exertion and rest as much as possible (NAVSEA, 2013b). To limit metabolic production of CO_2, survivors adhere to a low-calorie, high-fat diet which both minimizes the volume of food that must be digested and reduces survivors' respiratory quotient (NAVSEA, 2013c).

Increasing CO_2 levels during a DISSUB is a limiting factor for survivors in a DISSUB scenario awaiting rescue (Horn et al., 2009). As such, the NAVSEA 774 class guard book (NAVSEA, 2013c) stipulates that submariners must escape prior to CO_2 levels reaching 6% SEV. The rate at which this level is reached will depend primarily upon availability of LiOH stores, changes to the compartment pressure (see Increased compartment pressure section, pg. 11), and the number of survivors (NAVSEA, 2013c).

Air contaminants. During normal operations, the atmosphere of a submarine contains trace amounts of organic and inorganic contaminants (e.g., particulate matter, gases, vapors, and aerosols), which are cleaned from the atmosphere through continuous scrubbing and periodic ventilation (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). The discontinuation of air scrubbing and the inability to ventilate the boat during a DISSUB scenario means that there will be minimal capabilities to purge air contaminants once they are introduced in the atmosphere.

The nine potential air contaminants identified in Table 1 are ammonia, carbon monoxide, chlorine, hydrogen chloride, hydrogen cyanide, hydrogen sulfide, lithium hydroxide, nitrogen dioxide, and sulfur dioxide. Their potential sources and levels of exposure in a DISSUB scenario are discussed below. As is convention, quantities of air contaminants will be discussed in parts-per-million (ppm), which represents the number of contaminant molecules per every million gas molecules.

DISSUB-specific atmospheric limits. Submarine Escape Action Levels (SEALs) are the only DISSUB-specific atmospheric limits that provide guidelines for the concentrations of individual atmospheric contaminants at which survivability may be negatively affected (*Review of Submarine Escape Action Levels for Selected Chemicals*, 2002). SEALs have been defined for ammonia, carbon monoxide, chlorine, hydrogen chloride, hydrogen cyanide, nitrogen dioxide, and sulfur dioxide gases. While SEALs have been developed and proposed for hydrogen sulfide, they have not been formally adopted by the USN. No SEALs have yet been formally considered for lithium hydroxide.

SEALs consist of two thresholds defined for individual contaminants: SEAL 1 and SEAL 2. If SEAL 1 is exceeded, the atmosphere is considered breathable for up to 24 hours, provided that pressure and air contaminant levels remain stable. If SEAL 2 is exceeded at any point during the survival phase of a DISSUB scenario, the air is considered no longer safely breathable, and survivors are required to don EABs while additional escape decisions and actions are made.

In addition to the SEAL thresholds for individual gases, a subset of the potential air contaminates are identified as respiratory irritants (ammonia, chlorine, hydrogen chloride, nitrogen dioxide, sulfur dioxide), and therefore their effects are considered cumulative (NAVSEA, 2013c). The Cumulative Effect Index (CEI) is used to calculate CEI 1 and CEI 2. If CEI 1 or CEI 2 are reached, survivors are required to follow actions as if SEAL 1 or SEAL 2, respectively, has been reached for an individual contaminant. SEAL values are listed in

Appendix C as they define the range of exposure that submariners may experience in a DISSUB scenario.

Ammonia. At room temperature, ammonia (NH_3) is a colorless gas with a very distinct, pungent odor. NH_3 is considered a respiratory irritant, as it is highly corrosive when it comes in contact with moist or mucous surfaces (Agency for Toxic Substances and Disease Registry, 2004, 2014, October 21). On a submarine, NH_3 is found within the CO_2 scrubbers and sanitary tanks (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Since the CO_2 scrubbers will mostly likely be non-functioning in a DISSUB scenario, NH_3 is only likely to be introduced to the atmosphere either due to breach of sanitary tanks or as a byproduct of any fire(s) onboard the DISSUB (Brandt-Rauf, Fallon, Tarantini, Idema, & Andrews, 1988).

Carbon monoxide. Carbon monoxide (CO) is an odorless, tasteless, nonirritating, and colorless gas (Center for Disease Control and Prevention, 2018), which makes it difficult, if not impossible, to detect without equipment (*Acute Exposure Guideline Levels for Selected Airborne Chemicals*, 2010). Under normal operating conditions, the main source of CO on a submarine is from cooking with oils and fats in the galley (*Acute Exposure Guideline Levels for Selected Airborne Chemicals*, 2010). CO is also a natural component of exhaled air, occurring at a level of approximately 4 ppm for nonsmokers (Hung, Lin, Wang, & Chan, 2006). During normal operations, CO is managed through CO-H_2 burners, which are responsible for oxidizing CO and hydrogen (H_2) to CO_2 and water (H_2O). During a DISSUB scenario, the CO-H_2 burners will be non-functioning, and there will be no other means to remove CO from the atmosphere (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). While CO will not result from cooking during a DISSUB scenario, CO will continue to be produced through survivor respiration, and significant amounts of CO may be produced if fire(s) occur (Brandt-Rauf et al., 1988).

Chlorine. Chlorine (Cl) is a toxic gas that has corrosive properties and a strong odor resembling that of bleach (Center for Disease Control and Prevention, 2013). Cl itself is not flammable, but it can react explosively by forming compounds with other chemicals (Center for Disease Control and Prevention, 2013). Significant amounts of Cl may be produced in the case of battery compartment flooding resulting in contact between seawater and the submarine's battery terminals and bus work (Harvey & Carson, 1989; *Nuclear Powered Submarine Atmosphere Control Manual*, 2013). Relatively minor amounts of Cl may be introduced during a DISSUB scenario due to the burning of chlorate candles that are used to replenish O_2 in the boat atmosphere (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013).

Hydrogen chloride. Hydrogen chloride (HCl) is a colorless, nonflammable gas with a strong irritating odor (Agency for Toxic Substances and Disease Registry, 2002). HCl interacts with air and atmospheric water vapor to form dense, white, corrosive vapors and hydrochloric acid (Agency for Toxic Substances and Disease Registry, 2002). During a DISSUB, HCl may contaminate the atmosphere as a byproduct of any fire(s) present in a DISSUB scenario (Brandt-Rauf et al., 1988).

Hydrogen cyanide. Cyanides are a family of compounds containing the highly-reactive cyanide anion produced from both anthropogenic and natural sources; they are found in unpolluted air at concentrations of 0.160 - 0.166 ppm (Agency for Toxic Substances and Disease

Registry, 2006, July). The cyanide compound that is most commonly found in air is hydrogen cyanide (HCN). During a DISSUB scenario, HCN would be produced if a fire occurred (Brandt-Rauf et al., 1988; *Nuclear Powered Submarine Atmosphere Control Manual*, 2013).

Hydrogen sulfide. Hydrogen sulfide (H_2S) is a colorless, flammable gas that is highly toxic and has been described as having a pungent odor similar to that of rotten eggs (Occupational Safety and Health Administration, 2005). The compound H_2S is naturally found within natural gas, crude petroleum, and in the breakdown of sewage (human and animal; Occupational Safety and Health Administration, 2005). H_2S contamination may occur during a DISSUB scenario in cases in which submariners are not able to properly dispose of their sewage (i.e., trash cans lined with plastic bags will be used as latrines; NAVSEA, 2013c); existing sewage may also introduce H_2S to the atmosphere if the sewage tanks are breached. Significant quantities of H_2S will also be produced if organic material (including sewage) is burned. As it is heavier than air, H_2S may concentrate at lower compartments of the DISSUB (Occupational Safety and Health Administration, 2005).

Lithium hydroxide. During a DISSUB scenario, submariners will hang lithium hydroxide (LiOH) curtains as a passive means of removing CO_2 from the atmosphere (NAVSEA, 2013c). While LiOH is primarily encapsulated within the curtain matrix, LiOH dust may contaminate the atmosphere if the curtains are improperly handled resulting in tears. Fortunately, unlike other air contaminants, LiOH dust in the atmosphere rapidly disintegrates as it reacts with CO_2 (Horn et al., 2009). For example, although trace amounts of LiOH dust resulted from curtain deployment during the SURVIVEX experiments, all atmospheric LiOH dust dissipated within an hour (Horn et al., 2009). To mitigate the effects of LiOH dust exposure, personnel responsible for LiOH curtain deployment are provided with appropriate safety gear (e.g., face masks); however, bystanders without protection may be affected.

Nitrogen dioxide. Nitrogen dioxide (NO_2) is a normal constituent of the atmosphere and is generally released by means of industrial emissions or industrial processes that burn fossil fuel (United States Environmental Protection Agency, 2016, September 8). On a submarine, NO_2 is found within the CO_2 scrubbers (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013) and may be introduced to the atmosphere if the scrubbers are breached. Significant concentrations of NO_2 may also be introduced into the submarine atmosphere during a DISSUB if fire(s) occur (Brandt-Rauf et al., 1988).

Sulfur dioxide. Sulfur dioxide (SO_2) is a colorless gas with an irritating, pungent odor (National Institute for Occupational Safety and Health, 2016) that belongs to a group of gases called sulfur oxides (Agency, 2018). SO_2 would be produced during a DISSUB if any fossil fuels or other materials containing sulfur were burned in a fire (Brandt-Rauf et al., 1988; *Review of Submarine Escape Action Levels for Selected Chemicals*, 2002).

Increased compartment pressure. During normal submarine operations, the internal compartment pressure of a submarine is maintained at one atmosphere absolute (ata) to match the pressure exerted at surface (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). However, a DISSUB scenario poses several hazards that will cause the compartment pressure to rise (e.g., Horn et al., 2009; NAVSEA, 2013c; *Nuclear Powered Submarine*

Atmosphere Control Manual, 2013). A flooding event will increase pressure by filling compartment(s) with seawater, thus forcing the air to compress in order to fit within the reduced volume. For example, internal compartment pressure aboard the BAP Pacocha (SS-48) reached 2.6 ata over 17 hours in part due to flooding (SS-48; Harvey & Carson, 1989). Similarly, any scenarios which cause submariners to don EABs (e.g., in response to fire and/or air contaminants) will increase pressure since the additional air molecules added to the DISSUB atmosphere from the pressurized air bank must fit within the fixed compartment volume (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013).

Submariners exposed to hyperbaric pressure (i.e., pressure greater than surface atmosphere) for extended periods of time incur a decompression obligation that must be met in order to safely return to surface pressure (NAVSEA, 2013c). Safe decompression (i.e., gradually decreasing pressure allowing the body's physiology to safely adapt) can only be achieved with the appropriate rescue assets. Individuals who do not satisfy their decompression obligations (e.g., rapid ascension occurring from escape) are at a risk of developing decompression sickness (NAVSEA, 2013c). The NAVSEA SSN 774 class guard book (FWD) states that a 24-hour exposure to compartment pressure $\geq$1.70 ata increases the risk of developing decompression sickness upon returning to surface pressure. This risk increases with exposure to higher pressures and longer exposure durations (NAVSEA, 2013). At higher pressures, escape will no longer be an option, as survivors will be required to undergo decompression support from rescue assets to fulfill their decompression obligation. Five ata is considered the maximum survivable atmospheric pressure that can be reached aboard a DISSUB even with appropriate rescue assets (Whybourn et al., 2019).

In addition to imposing a decompression obligation, increased pressure can exacerbate the effects of CO_2 and air contaminants. The NAVSEA SSN 774 class guard book (FWD) states that "the physiological effect of a gas is a function of its partial pressure at depth, not the percentage of gas in the atmosphere" (NAVSEA, 2013c, pg. 14). This is because the number of molecules inhaled with each breath depends on both the pressure of the atmosphere and the composition of gases. For example, if CO_2 composes 2% of the atmosphere (0.02 $FiCO_2$), at normal atmospheric pressure (1 ata) individuals will inspire 2% CO_2 SEV (0.02 $PiCO_2$). However, if the percentage of CO_2 in the atmosphere remained the same (0.02 $FiCO_2$) but the pressure tripled (3 ata), then individuals would be breathing the equivalent of 6% CO_2 SEV (0.06 $PiCO_2$). In this way, increased compartment pressure would exacerbate the effect of air contaminants (see Air contaminants section, pg. 9) and CO_2 exposure (see Increased carbon dioxide levels subsection, pg. 8).

Additionally, increased compartment pressure introduces two unique stressors: increased oxygen partial pressure and increased nitrogen partial pressure.

Increased oxygen partial pressure. While oxygen availability is critical for survival in a DISSUB scenario, breathing an abundance of oxygen due to increased compartment pressure can be deleterious. Even though oxygen levels as a percentage of the atmospheric composition (FiO_2) will likely decrease during a DISSUB scenario (see Decreased oxygen subsection, pg. 7; NAVSEA, 2013c), increases in pressure can increase the risk of developing pulmonary oxygen toxicity (Vann, 1988). Common symptoms of pulmonary oxygen toxicity include respiratory discomfort, headache, and nausea (Eckenhoff, Dougherty, Messier, Osborne, & Parker, 1987). Pulmonary oxygen toxicity is likely to result from breathing oxygen partial pressures exceeding 0.5 PiO_2 for an extended period of time (Vann, 1988). This PiO_2 level could be reached in a

DISSUB scenario if, for example, O_2 makes up 18% of the atmosphere (0.18 FiO_2) and compartment pressure increases to 3 ata, resulting in 0.54 PiO_2. Oxygen toxicity can also develop more rapidly (i.e., within hours) at higher PiO_2 exposure levels (Van Ooij, Hollmann, van Hulst, & Sterk, 2013). Overall, the likelihood of developing pulmonary oxygen toxicity in a DISSUB scenario will depend on the magnitude of increase in pressure (ata), decrease in oxygen as a percentage of the atmosphere (FiO_2), and exposure duration.

Increased nitrogen partial pressure. Breathing at increased partial pressures increases the solubility of nitrogen in the body's tissue and may result in a reversible condition known as nitrogen narcosis (Schmidt, Hamilton, Moeller, & Chattin, 1975; Whitaker & Findley, 1977). While nitrogen narcosis may occur if compartment pressure rises during a DISSUB scenario, it is likely to be mild even at 4-5 ata, which is approximately the maximum survivable pressure of a DISSUB scenario (Weathersby, Survanshi, Parker, Temple, & Toner, 1999). Research suggests that previous exposure to hyperbaric conditions may reduce some symptoms of nitrogen narcosis (Hamilton, Laliberte, & Fowler, 1995; Moeller & Chattin, 1975); however, submariners in a DISSUB scenario are unlikely to have any recent substantive exposure that would be sufficient to impart any adaptation to nitrogen narcosis. Furthermore, there is no evidence for progressive or short-term adaptation to acute nitrogen narcosis events (Levett & Millar, 2008). While possible, increased nitrogen partial pressure is only likely to have an effect at the maximum survivable pressure of a DISSUB scenario.

Flooding. Flooding occurs when seawater enters the internal compartment(s) either through or open hatches or penetrations in submarine structure, such as due to breach of the hull or failure of a seawater piping system. Submariners are well-trained to immediately take action to stop flooding events (*Study of Submarine Casualty Control Training*, 1966). Flooding must be contained before the entire hull is filled with seawater, or the submarine will reach a point of no recovery and the crew must escape in order to survive. While isolating the flooding incident, submariners may experience submersion (i.e., being completely underwater) or immersion (i.e., partially underwater). Survivors who become wet through immersion/submersion or contact with water through any spray leaks are likely to remain wet for a prolonged period of time.

One concern in a DISSUB scenario is the possibility of slow, progressive flooding from many small leaks that cannot be identified and stopped. This could occur from hundreds of penetrations through the watertight bulkhead used as conduits for electric cables, ventilation, and other high and low pressure piping systems (A. Quatroche, personal communication, October, 16, 2018). A small leak from even a few of those penetrations would, over time, cause a progressive increase in the level of flooding that cannot be sufficiently mitigated while waiting for rescue (A. Quatroche, personal communication, October, 16, 2018).

In addition to submersion and immersion, a flooding event will likely expose individuals to other stressors: the compartment pressure will steadily increase if progressive flooding is not stopped (see Increased compartment pressure section, pg. 11); exposure to cold seawater can induce hypothermia even after the flooding event has been stopped (see Thermal section, pg. 5); flooding may result in harmful chlorine gas entering the atmosphere if seawater enters the battery compartment (see Chlorine subsection, pg. 10); and survivors may experience various mental stressors, such as hopelessness (see Hopelessness section, pg. 17) and coping with death of shipmates in the flooded compartments (see Death of shipmates section, pg. 16).

Lighting. In the likely event of power loss during a DISSUB scenario, the white fluorescent light fixtures that normally illuminate compartment spaces (Luria, 1987; Young et al., 2015) will be inoperable (NAVSEA, 2013c). Emergency lighting and battle lanterns in some critical watchstanding areas are fitted with red color filters which will illuminate the cabins (A. Quatroche, personal communication, October, 16, 2018). While these alternative lighting sources are available, illumination will not be near that experienced under normal operations. For example, although chemical light sticks provided sufficient illumination for watchstanders recording logs under DISSUB conditions (Horn et al., 2009), they had reduced illumination after four hours and became completely ineffective after 12 hours (Horn et al., 2009). Further, this was under optimal air quality conditions; illumination from alternative lighting sources may become drastically less effective if the atmosphere is compromised by contaminants such as smoke.

Fire. Fire(s) on a submarine pose a large threat to the integrity of the boat and the submariners aboard. Based on past submarine DISSUB incidents and casualties (e.g., BAP Pacocha (SS-48; Harvey & Carson, 1989) and USS Bonefish (SS-582; Commander Submarine Force U.S. Atlantic Fleet, 1988)), fires are most likely to start due to electrical short circuiting of damaged equipment. Although fires are most likely to occur earlier in a DISSUB scenario as the cause or direct effect of inciting event, fires may occur later in a DISSUB scenario due to improper use of oxygen candles and high pressure lubricating oil leaks (A. Quatroche, personal communication, October, 16, 2018). Fires are multifactorial events that have the potential to adversely affect submariners through several means. For example, depending on the composition of the materials that are burned during a fire, a variety of harmful air contaminants may be introduced to the atmosphere (see Air contaminants section, pg. 9; Brandt-Rauf et al., 1988). Additionally, fire(s) will quickly deplete O_2 levels within the submarine atmosphere (see Decreased oxygen levels subsection, pg. 7).

At the first indication of fire, submariners are trained to don EAB masks to protect themselves from the effects of smoke and toxic gases (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). During normal submarine operations, the boat is able to ascend to periscope depth and exchange air with the surface atmosphere once the fire has been extinguished; however, in a DISSUB scenario, the smoke and any other toxic gases will remain in the compartment as there will be no method to remove the smoke or atmospheric containments. Though EAB masks help to protect survivors from smoke and air contaminants, EAB use has three major adverse effects. First, each of the EAB masks in use will add approximately 20 standard cubic feet (scf) of air to the compartment each hour (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013); with a large number of survivors (>20), the compartment pressure will quickly rise and reach the 23 feet seawater pressure limit (1.7 ata; NAVSEA, 2013c) at which survivors must escape within 24 hours to limit their risk of experiencing decompression sickness (see Increased compartment pressure section, pg. 11). The second adverse effect of EAB usage is that the air is drawn from the same air banks that provide pressurized air necessary for operation of the escape system. Use of the EAB system by a large number of survivors will reduce air pressure in the submarine's service air bank at a rapid rate, and if the air bank pressure is reduced too much then it will not be possible to operate the escape trunk (NAVSEA, 2013c). Lastly, using EABs reduces the mobility of the crew. Each EAB station is permanently installed, and each EAB mask is attached to an 8 ft. hose connected to a station (*Nuclear Powered Submarine Atmosphere Control Manual*, 2013). While EAB hoses can be rapidly disconnected and re-connected to different stations, the ability to move about the compartments can be hindered when connected.

Another hazard posed by fires is direct radiant heat along with a rapid increase in compartment temperature. The pressure hull of a submarine is a ring-stiffened cylinder design in which the internal frames act as a chimney, moving heat and flames vertically between decks in the event of a fire (A. Quatroche, personal communication, October, 16, 2018). As such, fires can spread rapidly across decks, depositing heat and smoke in the upper levels of a compartment and potentially raising the compartment temperatures to unsafe conditions (see Thermal section, pg. 5). Those who are unable to don protective firefighting equipment (i.e., due to limited quantity) may receive burn injuries (see Pain/injury section, pg. 18; Zawacki, Jung, Joyce, & Rincon, 1977). However, even the protective gear itself can pose issues, as the restrictive clothing prevents vapor permeability, leading to a decrease in the evaporative heat loss required to maintain core body temperature at safe levels (Enander & Hygge, 1990; Hancock, 1982; Mclellan & Selkirk, 2006). These heat conditions, in conjunction with the physically-demanding tasks required of fire-fighting survivors (i.e., lifting and carrying heavy equipment; Gledhill & Jamnik, 1992), can exacerbate the likelihood of developing thermal stress (see Thermal section, pg. 5).

Noise. During normal submarine operations, machinery noise generated by the boat's engines, fuel pumps, air conditioning systems, and other mechanical sources all contribute to the ambient noise level within the submarine. In the likely event of a power loss during a DISSUB scenario, most of the machines that produce noise will cease to operate; therefore, the noise levels that are present during a DISSUB will be substantially lower, though the exact levels are currently unknown. In the absence of machine-generated noise, survivors in a DISSUB scenario will experience inordinately low ambient noise levels aboard the submarine. Verbal communication among survivors may be the primary source of sound after the inciting event has occurred and any hazard(s), such as a fire or flooding, have been mitigated. When survivors need to communicate with rescue crews, tapping on the hull may be required if power is not available to operate the underwater telephone (NAVSEA, 2013c), introducing sharp, intermittent sounds.

Radiation. In 1954 the USS Nautilus (SSN-571) became the first submarine powered by a nuclear reactor (all prior submarines were powered by conventional diesel-electric engines; Naval History and Heritage Command, 2018, June 22). Nuclear-powered submarines have since become the norm in the United States because they have the capability to conduct longer underway missions, surface less frequently, and operate at higher speeds for longer periods of time than submarines powered by other fuel sources (*Over 157 Million Miles Safely Steamed on Nuclear Power*, 2015; Walker & Krusz, 2018). Despite operating in close proximity to nuclear reactors, submariners are exposed to substantially less radiation while underway compared to normal industrial activities and daily surface life (Mueller, Weishar, Hallworth, & Bonamer, 2018).

Nuclear submarine reactors are equipped with automatic safety systems that are responsible for shutting down the nuclear reactor if the integrity of the reactor core is compromised; at this time, a fission reaction should no longer occur (A. Quatroche, personal communication, October, 16, 2018). In the event of a DISSUB, survivors must determine if the reactor has been properly shut down and ensure that there are no leaks or other damage to the reactor compartment shielding. If an inciting event causes damage to the nuclear propulsion or weapons systems, survivors may be exposed to ionizing radiation or radioactive contamination (Mueller et al., 2018). The degree of exposure will vary greatly depending on the extent of damage that occurs.

Mental Stressors

Confinement/isolation. Even during routine operations, submariners must cope with prolonged periods of confinement and isolation from the surface world (e.g., Beare, Biersner, Bondi, & Naitoh, 1981; Moes & Lall, 1996; Weybrew, 1971). As such, the importance of identifying resilient individuals who can adapt to the submarine environment and providing appropriate training is a major goal of the USN (Whanger, Bing, America, Lamb, & Severinghaus, 2008). To limit future unplanned losses, every effort is made to screen out any individuals with potential claustrophobic tendencies who may not be able to adapt to the confined conditions of submarine service (Bing, America, Lamb, & Severinghause, 2005; Schlichting, 1993).

While trained submariners are expected to be tolerant of confined conditions, the mental stress of confinement may be amplified during a DISSUB scenario. During normal operations, the stress of confinement is likely mitigated by mission-length expectation (i.e., there is a set timeline for return to port). The unexpected nature of a DISSUB scenario will drastically disrupt this timeline, as submariners will be confined within the DISSUB without a certain timeline for escape or rescue. This situation may inspire a heightened awareness of their confinement and exacerbate any negative feelings of being trapped. Additionally, communication with the surface world may be minimal or nonexistent, adding to the isolation felt by survivors.

In addition to psychological factors magnifying the effects of confinement, the physical space available within the submarine may be reduced. Any damage to the hull, flooding, or fire may limit the compartments accessible to survivors, which would reduce the amount of space aboard the submarine. For example, in the sinking of the BAP Pacocha (SS-48), 22 survivors became trapped together in the FWD torpedo room due to flooding of the other compartments (Harvey & Carson, 1989). This degree of confinement is beyond what survivors would have previously experienced during normal submarine operations and may surpass their tolerance.

Death of shipmates. The inciting event of a DISSUB scenario is likely to result in crew member casualties. Additionally, while many crew members are expected to survive the initial DISSUB inciting event, there is still the potential that they may not survive to be rescued either from the submarine or at the surface following an escape. A review of historical DISSUB events with survivors (i.e., the review did not consider any DISSUB events in which none of the crew members survived) suggests that a mean of 66.4% of crew are alive following the inciting event of a DISSUB scenario; however, only a mean of 46.3% of the crew ultimately survive through escape or rescue (Whybourn et al., 2019). These numbers vary based on the inciting event, with systems failures having the lowest historical survival rate (26.6% survive after the inciting event and 26.3% ultimately survive) and collision having the highest historical survival rate (65.7% survive after the inciting event and 55.6% ultimately survive; Whybourn et al., 2019).

In the event of crew death aboard the DISSUB, surviving crew members may be required to handle their former shipmates' dead bodies. The DISSUB guard book directs survivors to isolate dead bodies and dismemberments as soon as possible to minimize the proliferation of harmful bacteria (NAVSEA, 2013c). However, as other survival efforts (e.g., mitigating fires) take precedence over the management of bodies, bodies may not be able to be moved until after the condition of the submarine is assessed. As such, survivors may have to cope with seeing deceased shipmates for some time, then may also have to directly handle their dead bodies and/or dismembered body parts. In other scenarios, survivors may be trapped in a compartment with dead bodies with no means to separate themselves from exposure.

Hopelessness. Given the life-threatening nature of a DISSUB scenario (see Death of shipmates section, pg. 16), survivors may experience hopelessness—wondering whether or not they will survive the situation to ever see their friends and family again.

The USN requires every boat to contain crew members who have successfully completed a course in DISSUB survivor training. Through this course, submariners learn how to utilize the DISSUB guard book to correctly oversee the onboard survival phase and execute escape procedures. In a DISSUB scenario, a survivor who has completed this training is designated as the senior survivor and assumes leadership over the remaining crew. However, only a portion of the crew will have completed the training (A. Quatroche, personal communication, October, 16, 2018), so in a DISSUB scenario with a highly lethal inciting event, it is possible that none of the survivors will have completed any DISSUB training. These survivors may lack confidence when executing the unfamiliar DISSUB procedures, which could cause them to experience feelings of hopelessness.

Hopelessness may occur even if there are survivors with qualified DISSUB training. During the 1944 sinking of the USS Tang (SS-306), survivors were initially confident and enthusiastic in their ability to follow escape procedures; however, after a realization of the dangers and the life-threating nature of the event, their confidence began to diminish even among individuals who were well-trained (United States Navy, 1949). As the onboard survival phase progressed, the survivors aboard the USS Tang expressed apathy toward escape after realizing the severity of the situation (United States Navy, 1949).

Feelings of hopelessness may be exacerbated in the case of a “deep” DISSUB situation (ship depth >600 ft.). In such scenarios, escape is not an option even if the conditions aboard the DISSUB become unsafe, and rescue becomes the only possibility for survival (NAVSEA, 2013c). During the waiting period, survivors may have no indication that rescue assets have been organized or even that anyone else knows of their sinking. The survivors may feel that they have minimal or no control over their own fates, which is likely to result in increased hopelessness (Prociuk, Breen, & Lussier, 1976).

Boredom. In a DISSUB scenario, waiting for rescue is always the preferred course of action as long as conditions aboard the DISSUB remain tolerable (NAVSEA, 2013c). Once the inciting event has subsided and any hazards, such as a fire or flooding, have been mitigated, survivors will be in a period between excitement and potential future hopelessness. During this period, boredom may set in.

Entertainment in the form of card games or books may be available to survivors if they had brought them underway and if they are in an accessible compartment. However, individuals in previous simulated DISSUB research reported that it soon became difficult to concentrate when reading books (Slaven & Windle, 1999). Thus, survivors may not be able to effectively engage with these items to alleviate boredom.

Survivors who are ordered to rest in order to minimize O_2 consumption, CO_2 production, and exothermic output (NAVSEA, 2013c) may experience the most significant boredom. Although crew members under normal operations are subjected to monotonous tasks and limited external stimulation (Maeland & Brunstad, 2009), boredom may be magnified in a DISSUB scenario in which some survivors may have no assigned operational tasks. However, it should be noted that feelings of boredom are most likely to be experienced by individuals who are not in the position of making critical decisions (i.e., not the senior survivor). Therefore, boredom may have a minimal effect on survival efforts.

Conflict among crew members. Mission success within the submarine force is predicated upon submariners working successfully as a team. As such, there is a strong interdependent relationship among submariners while underway. The thoughts, feelings, and actions of individual crew members have the potential to substantially impact the overall group dynamic and influence one another's emotional and behavioral outcomes (Forsyth, 2014). Due to the inherently stressful conditions of submarine work, submariners are known to have a high degree of group coherence, even when sub-groups are present within the crew (Kimhi, 2011).

Conflict may arise if survivors perceive a specific individual or group of individuals as being at fault (e.g., a mistake made during watchstanding or maintenance contributed to the DISSUB event). However, even in the absence of a clear target of blame, group coherence in a DISSUB scenario will likely be challenged by the stress of the situation, potentially resulting in interpersonal or intragroup conflict among crew members.

Survivors will be required to operate while under impaired health states that are associated with increased irritability, such as caffeine withdrawal (see Caffeine withdrawal section, pg. 20) and hunger (see Nutrition section, pg. 19). Increased irritability will likely lead to increased social tension, social withdrawal, and decreased cohesiveness (Palinkas, 2001). While the crew's overarching mission is to survive, negative emotions due to hopelessness and disagreements among survivors may result in varying lines of opinions on how to proceed with the unique situation. For example, a portion of survivors may want to immediately initiate escape procedures even if the senior survivor determines escape is not advised based on objective criteria. Significant sentiments of tension and anger attributed to stress among the survivors could lead to interpersonal conflict and a breakdown in the chain of command during a DISSUB scenario.

Physical Stressors

Pain/injury. Many DISSUB inciting events, such as a collision (e.g., BAP Pacocha (1988; Harvey & Carson, 1989); USS Stickleback, (1958; Barron, 2002)) or fire are likely to injure submariners. In an analysis of historical, survivable DISSUB events that resulted in rescue or surface abandonment, approximately 1% of the crew were found to have suffered musculoskeletal trauma resulting from blast or major blunt force during the inciting event, with individual case incidence rates ranging up to 12.5% for blast trauma and 2.2% for major blunt force trauma (Whybourn et al., 2019). Additionally, approximately 1% of the crew became injured from burns, depending on the type of inciting event (Whybourn et al., 2019). While adrenaline may decrease the perception of pain (Metaxotos, Asplund, & Hayes, 1999) in injured individuals during the initial stages of DISSUB scenario, as adrenaline fades, injured submariners are likely to experience inflammatory pain (Barbe & Barr, 2006; Pedersen, 2000).

In addition to inflammatory pain, submariners in a DISSUB scenario may also experience pain from headaches resulting from CO_2 exposure (Law, Watkins, & Alexander, 2010), head injury (Hoffman et al., 2011), caffeine withdrawal (Juliano & Griffiths, 2004), dehydration (Blau, Kell, & Sperling, 2004), and caloric restriction (Mosek & Korczyn, 1999) among other potential causes. While the underlying physiology of these various headaches may differ, the pain percept is similar and may have a similar effect on cognition and performance. During SURVIVEX 2004, 47.9% of participants reported experiencing a headache during the exercise, with 77.1% of those affected describing the pain as severe at times (Horn et al., 2009).

Survivors may also experience a dull continuous pain in the form of hunger. During a DISSUB scenario, survivors are expected to only eat enough to avoid feelings of starvation but to remain hungry (NAVSEA, 2013c). This hunger may result in feelings of dull pain often referred to as hunger pangs (Cannon & Washburn, 1912).

Nutrition. In a DISSUB scenario, the food intake and nutrition patterns submariners experience are substantially altered relative to what is experienced during normal submarine operations. Submariners will be required to decrease the volume of food consumed in order to reduce CO_2 production occurring due to metabolic activity (NAVSEA, 2013c). While the guard book does not prescribe a specific caloric limit, it does state that "the amount of food eaten by each survivor should be restricted so that they remain hungry (but not starving)" (NAVSEA, 2013c, Appendix A-1 (Sheet 1)). Laboratory DISSUB simulations have provided participants with approximately 1100 kcal/day (Risberg et al., 2004). Overall, this diet is likely to result in survivors running a caloric deficit, though exact energy demands are likely to vary based on the DISSUB conditions (e.g., compartment temperature) and individual metabolic needs (NATO, 2017).

In addition to the caloric restrictions imposed by the DISSUB diet, sailors are also instructed to ingest high-fat foods, because they are more calorically-dense than foods primarily consisting of carbohydrates or protein (NAVSEA, 2013c). Thus, smaller volumes of high-fat foods need to be digested to provide the required amount of energy. Within this low-calorie, high-fat DISSUB diet, there is a specific priority order that foods are to be consumed: 1) cooked, chilled food (e.g., cold cuts and cheeses); 2) cooked, frozen food (food should be kept in the freezers for the first 48 hours of the DISSUB situation and access should be minimized to prevent the food from thawing); 3) fresh food (but foods that require washing should only be consumed if there is sufficient water for that purpose); 4) canned foods; 5) dry foods (only if all other food sources are depleted or are unsafe to eat due to risk of food poisoning). This prioritization of food usage is designed to minimize the risk of unsafe food consumption given that no cooking should be performed to minimize the buildup of heat (see Thermal section, pg. 5; NAVSEA, 2013a).

Insufficient water intake. Water comprises approximately 60% of the body mass of healthy young adults and is essential for supporting the physiological processes vital for life (Jéquier & Constant, 2010). Water is used throughout the body to support chemical reactions and as a transport for nutrients, gases, and hormones, among other uses (Thomas & O'Brien, 2008). Throughout the day, the body loses water through respiration, sweat, and waste excretion. Dehydration occurs when water intake is insufficient to replace the water that is lost through these processes.

There are multiple factors that may contribute to submariners becoming dehydrated in a DISSUB scenario. One factor is that body water lost through sweat may increase due to the increased compartment temperature and humidity. The body continuously loses water via perspiration, with amounts lost varying based on external heat and humidity, as well as the activity level of the individual. Under normal, sedentary conditions, water lost through sweat is approximately 0.3 L/hr; sweat output can increase to 2 L/hr when individuals are exposed to extreme heat (Popkin, D'Anci, & Rosenberg, 2010; Sawka, Muza, & Young, 2008). The likely increase in temperature during a DISSUB scenario (see Thermal section, pg. 5) will render submariners highly susceptible to dehydration from increased sweat loss.

A second factor that may contribute to the occurrence of dehydration in a DISSUB scenario is that crew members may neglect their thirst response due to stress (Herman, Polivy, Lank, & Heatherton, 1987). To prevent dehydration, the body incites a desire to drink (i.e., regulatory thirst) in the individual through a complex system of physiological triggers. Osmoreceptors in the brain are sensitive to when cells shrink as a result of dehydration and incite regulatory thirst to motivate water intake (Bourque, Oliet, & Richard, 1994). Although there is controversy over whether satisfying thirst is sufficient for maintaining sufficient hydration (Armstrong, Johnson, & Bergeron, 2016; Hoffman, Cotter, Goulet, & Laursen, 2016), evidence suggests that satiating thirst is generally sufficient for young, healthy individuals at rest (Casa, Clarkson, & Roberts, 2005). However, previous research has indicated that stress can alter the way that individuals respond to satiety. When exposed to stress, some individuals neglect natural feelings of satiety and subsequently do not consume enough to fulfill their bodily needs (Herman et al., 1987; Kivimäki et al., 2006). That is, under stressful conditions such as a DISSUB scenario, individuals may be distracted due to stress and may fail to properly attend to their regulatory thirst impulse. To compensate for this, the DISSUB guard book recommends that "a designated individual should be given the responsibility of ensuring that each survivor consumes adequate quantities of fluid" (NAVSEA, 2013c, Appendix A-1 (Sheet 2)).

Another factor that may lead to dehydration among DISSUB survivors is that water intake via food consumption will be limited. A U.S. survey estimated that approximately 20% of individuals' water intake comes from food sources (Ershow & Cantor, 1989), with fresh fruits and vegetables providing the highest water content (Altman & Katz, 1961). In a DISSUB scenario, the volume of food consumed is limited (see Nutrition section, pg. 19), and the foods that are prioritized for consumption are generally lower in water content (NAVSEA, 2013c). Both of these factors will likely limit the water that submariners receive via food. While limited water intake from food sources may not be a primary cause of dehydration in a DISSUB scenario, it may have a meaningful impact in submariners who are already predisposed to dehydration due to other factors (e.g., see Thermal section, pg. 5).

Caffeine withdrawal. Caffeine is the most widely used psychoactive drug in the world, and is typically consumed as a component of coffee, tea, soft drinks, and energy drinks (Gilbert, 1984). National surveys indicate that approximately 89% of adult men in the U.S. report regular caffeine consumption, with average daily intake of approximately 196-211 mg per day (Ahuja, Goldman, & Perloff, 2006; Drewnowski & Rehm, 2016; Frary, Johnson, & Wange, 2005; Fulgoni, Keast, & Lieberman, 2015; Mitchell, Knight, Hockenberry, Teplansky, & Hartman, 2014). A survey of caffeine consumption patterns among active duty Naval personnel indicated a similar prevalence of regular caffeine consumption among Naval men (87%) compared to U.S. civilian men (Knapik et al., 2016). However, the average daily intake of caffeine was higher among Naval men (232 mg/day) compared to U.S. civilian men (196-211 mg/day; Knapik et al., 2016). Results also indicated that average daily caffeine intake for Navy personnel was positively correlated with age and rank, such that older, senior officers consumed the most caffeine on average. While the survey did not specify prevalence and mean intake values for submariners specifically, there is little evidence to suggest that caffeine consumption patterns are substantially different in a submariner population compared to general Navy servicemen. Thus, it can be expected that regular caffeine consumption in the submariner population is both highly prevalent and that average daily intake values are relatively high (the equivalent of approximately three 8 oz. cups of brewed coffee).

In a DISSUB scenario, sources of caffeine are likely to be highly limited or completely unavailable. Normal kitchen operations are suspended, and caffeinated beverages (i.e., the primary source of caffeine among Naval personnel) will not be available (Knapik et al., 2016). Emergency kits contain caffeine pills; however, supplies will be limited, and emergency kits may be inaccessible to portions of the crew in some situations. For these reasons it can be expected that submariners in a DISSUB scenario may be forced to abruptly cease their regular caffeine intake.

Due to the psychoactive nature of caffeine, it produces physical dependence following chronic use and subsequent withdrawal when no longer consumed (Strain, Mumford, & Silverman, 1994). The incidence and severity of the effects of caffeine withdrawal vary based on how much caffeine one typically consumes; however, research suggests that individuals who typically consume as little as 100 mg/day may experience withdrawal symptoms following cessation (Evans & Griffiths, 1999; Griffiths et al., 1990). The effects of caffeine withdrawal (most commonly headaches, fatigue, and reduced alertness; Juliano & Griffiths, 2004) vary in magnitude among individuals and depend on one's maintenance dose. The effects are so pronounced that Caffeine Withdrawal Syndrome has been added to the list of substance abuse disorders in the most recent version of the Diagnostic and Statistical Manual of Mental Disorders (American Psychiatric Association, 2013). In summary, caffeine withdrawal, with minimal means of mitigation, will likely be highly prevalent among the survivors in a DISSUB scenario.

Fatigue. While the exact neurobiological function of sleep is unknown, it is evident that sleep is necessary for wellbeing and survival (Everson, Bergmann, & Rechtschaffen, 1989; Rechtschaffen, Bergmann, Everson, Kushida, & Gilliland, 1989). While the optimal sleep duration for most individuals is 7-9 hours per night, a survey of over a million individuals revealed that 52.4% of Americans report getting less than 7.5 hours of sleep per night (Kripke, Garfinkel, & Wingard, 2002). This chronic sleep deprivation leads to fatigue and degradation of health and quality of life (Antunes, Levandovski, Dantas, Caumo, & Hidalgo, 2010; Bonnet & Arand, 1995; Spiegel, Leproult, & Van Cauter, 1999). Fatigue is already prevalent among underway submariners in normal conditions. In a survey of enlisted submariners, 45% of individuals reported "often," "frequently," or "always" being tired while on watch, and 60% reported "rarely" or "never" feeling well rested (Blassingame, 2001). See Chabal et al. (2018) for a review of sleep and fatigue in a normal submarine environment.

Fatigue is likely to become exacerbated in a high-pressure DISSUB situation. At the onset of a DISSUB scenario, there may not be time to sleep due to the critical need to respond to the inciting event that caused the DISSUB situation and its immediate fallout (e.g., extinguishing fires, stopping leaks, making temporary repairs to equipment, etc.). This can potentially result in acute sleep deprivation (e.g., being awake >24 hours). However, even after the situation is stabilized and the survivors are awaiting rescue, submariners are unlikely to achieve sufficient sleep. The stress of a DISSUB scenario can lead to an increase in stress hormones such as cortisol, which may make it difficult to sleep (Buguet, 2007). Individuals are likely to experience stress due to mental factors (e.g., see Hopelessness section, pg. 17), environmental factors (e.g., see Thermal section, pg. 5), and physical factors (e.g., see Pain/injury section, pg. 19); all of these are likely to preclude survivors from achieving sufficient sleep and will likely result in chronic fatigue (i.e., multiple nights in a row of a suboptimal sleep duration). During the SURVIVEX exercises, individuals did not receive sufficient sleep despite being given ample opportunity for rest (Horn et al., 2009). This was true even though individuals were not subject to the mental stressors that would likely be present in a real DISSUB scenario.

Poor hygiene. A DISSUB situation is likely to expose submariners to conditions of poor sanitation and/or lack of safe hygiene. The likely loss of power in a DISSUB situation will render the plumbing system disabled (NAVSEA, 2013c). If the sanitary system is operational, survivors are instructed to minimize flushing to no more than once every three bowel movements (NAVSEA, 2013c). If toilet facilities cannot be used (e.g., if they have become inaccessible due to flooding casualties), the crew will be required to use trash cans lined with plastic bags as latrines (NAVSEA, 2013c). This suboptimal disposal of sanitary waste will potentially introduce harmful bacteria into the environment.

Submariners might additionally be exposed to harmful bacteria from decomposing bodies and/or dismembered body parts (see Death of shipmates section, pg. 16). While, survivors are directed to isolate dead bodies as soon as possible (NAVSEA, 2013c); however, survivors may experience varying amounts of exposure if, for instance, they become entrapped within a compartment without any way of isolating decomposing bodies/dismembered body parts. Additionally, an average of 5.3% (range 0% to 83.7%) of the crew from historical, survivable DISSUB events were injured, and these injuries may provide a more direct exposure pathway through which bacteria can affect survivors (Whybourn et al., 2019).

Means of minimizing the spread of bacteria and infection will be limited in a DISSUB scenario. Electricity for bathing and washing facilities will most likely be compromised, and water suitable for drinking and cleaning will be limited (NAVSEA, 2013c). For these reasons there will likely be a proliferation of harmful bacteria during a DISSUB scenario due to increased exposure to bacteria and decreased sanitation capabilities.

Conclusion

This report is part of a series of two that intends to identify the stressors that may occur in a DISSUB scenario, review each stressor's potential cognitive effects, and assess how these cognitive effects could impair submariner operations during the onboard survival phase of a DISSUB scenario. In the current report (Part 1) we identified DISSUB stressors and categorized them as environmental, mental, or physical in origin. We accomplished this by reviewing DISSUB operational and scientific literature and conducting interviews with DISSUB subject matter experts. A myriad of stressors that originate from the environment (e.g., air contaminants, flooding, fire), mental stressors (e.g., boredom, hopelessness), and physical stressors (e.g., caffeine withdrawal, change in nutrition) were identified. Identified stressors were categorized as environmental, mental, or physical in origin, and each stressor was individually discussed regarding its potential source(s) of origin. Where appropriate we discussed the stressor's likelihood of occurrence and the degree of exposure that submariners may experience over the course of a DISSUB scenario.

In Part 2 (Reinhart, Chabal, Bohnenkamper, & Moslener, in preparation) we discuss the cognitive domains that are likely to affect operational success in a DISSUB scenario. We then conduct a literature review to examine what is known about how each DISSUB stressor is likely to affect submariner cognition, and highlight key knowledge gaps for future empirical research. Results of these empirical studies will provide critical information regarding submariner cognition and performance in DISSUB scenarios and how survival is likely to be affected. This information can then be rapidly transitioned through modifications to the DISSUB guard book, updating the Senior Survivor course, and dissemination to the fleet.

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Appendices

Appendix A: DISSUB-specific compiled literature

Title	Year	Source Type	Author
Theoretical considerations of the use of the air-filled submarine escape appliance from great depths	1952	NSMRL Technical Report	H. J. Alvis
Submarine escape, immersion and exposure suit	1956	NSMRL Technical Report	S. B. Rentsch
Submarine casualties booklet	1966	U.S. Naval Submarine School Report	U.S. Naval Submarine School, New London, CT
Elevated CO2 levels in air used to pressurize escape trunks as a limiting factor in depth of escape capability	1970	UMO Thesis	D. McMillan
International workshop on escape and survival from submersibles	1974	NSMRL Technical Report	NSMRL, Office of Naval Research, and Bureau of Medicine and Surgery Department of the Navy, Washington, D. C.
Submarine escape training in the U.S.: A re-evaluation	1974	UMO Thesis	T. S. Neuman
Submarine escape and rescue in 1980	1980	UMO Thesis	R. G. Eckenhoff
Pressurized submarine escape	1984	NSMRL Technical Report	R. G. Eckenhoff
Evaluation of the submarine escape immersion suit	1984	UMO Thesis	A. R. Manalaysa and V. A. Cassano
The B.A.P. Pacocha (SS-48) collision: The escape and medical recompression treatment of survivors	1989	NSMRL Special Report	C. Harvey and J. Carson
Submarine escape and rescue capabilities in 1989	1989	UMO Thesis	D. M. Mole
Disabled submarine rescue protocol development: Saturation diving, accelerated decompression using oxygen, pulmonary function monitoring, and decompression sickness	1999	UMO Thesis	J. Maurer
Use of emergency evacuation hyperbaric stretchers (EEHS) in submarine rescue	1999	UMO Thesis	G. W. Latson

Title	Year	Source Type	Author
Feasibility of using commercial-off-the-shelf ruggedized laptop computers and independent power sources in a disabled submarine	2001	NSMRL Technical Report	R. S. Kargher, S. J. Ryder, D. D. Wray, R. D. Woolrich, and W. G. Horn
Disabled submarine entry team: Rescue of survivors underwater	2001	UMO Thesis	B. Mecklenburg
Review of Submarine Escape Action Levels for Selected Chemicals	2002	Book	
Estimated carbon dioxide production and physiological adaptation of survivors in a simulated disabled submarine	2002	NSMRL Technical Report	T. J. R. Francis, A. J. Young, D. A. Stulz, S. R. Muza, J. W. Castellani, R. W. Hoyt, J. P. Delany, A. Cymerman, H. R. Lieberman, C. O'Brien, L. A. Blanchard, D. W. DeGroot, D. D. Wray, and W. T. Norfleet
Heat stress protocols for submarine escape guard books	2003	UMO Thesis	T. J. Ochsner
Submarine rescue diving and recompression system (SRDRS) decompression & manning plan proposal	2005	UMO Thesis	G. DeMers and K. W. Lehnhardt
Results of pressure testing AN/PDQ-1 RADIAC set (multi-function RADIAC) (RADICMETER IM-265/PDQ) in simulated conditions expected in a pressurized disabled submarine	2007	NSMRL Technical Report	A. J. Quatroche and W. G. Horn
Evaluating improved non-powered carbon dioxide scrubbing technologies	2007	NSMRL Technical Report	J. Vanderweele, L. M. Hughes, and W. G. Horn
An evaluation of casualty egress and patient stretchers for use on U.S. Navy submarines	2008	NSMRL Technical Report	W. G. Horn, J. D. Reed, A. J. Quatroche, and S. Wagner
Location and triage of disabled submarine (DISSUB) survivors: Validating equipment and procedures	2008	NSMRL Technical Report	J. Gertner, C. A. Duplessis, and W. G. Horn

Title	Year	Source Type	Author
Assessment of headache incidence during SURVIVEX 2004	2009	NSMRL Technical Report	G. DeMers, W. G. Horn, and L. M. Hughes
Submarine surface abandonment trials	2009	NSMRL Technical Report	N. J. Yarnall, W. G. Horn, and L. M. Hughes
Summary: Disabled submarine heat stress conference	2009	NSMRL Technical Report	W. G. Horn
SURVIVEX 2003 and SURVIVEX 2004: Simulated disabled submarine exercises	2009	NSMRL Technical Report	W. G. Horn, P. Benton, L. M. Hughes, G. Demers, C. J. Jankosky, P. Woodson, T. Lunney, S. L. Wagner, A. Quatroche, and D. Burnside
Optimal DISSUB interior hull tap locations for underwater communications between survivors and rescue forces	2010	NSMRL Technical Report	W. G. Horn, M. Keller, S. Reini, J. Vanderweele, and A. Quatroche
OPLAN 2137 [Rev A] Medical Services	2010	Other Policy Document	ANNEX Q to COMSUBLANT/COMSUBPAC
Seven day disabled submarine (DISSUB) survivability life support stores requirements	2010	Other Policy Document	Advanced Undersea Systems Program Manager (PMS 394)
Nuclear Powered Submarine Atmosphere Control Manual (S9510-AB-ATM-010)	2013	Manual	Naval Sea Systems Command (NAVSEA)
SSN 774 Class Guard Book Distressed Submarine Survival Guide Forward (Lockout Trunk)	2013	Guard Book	Naval Sea Systems Command (NAVSEA)
Technical and medical standards and requirements for submarine survival and escape [Edition A Version 1]	2014	NATO Policy Document	North Atlantic Treaty Organization (NATO)
The submarine search and rescue manual	2017	NATO Policy Document	North Atlantic Treaty Organization (NATO)

Appendix B: Identified stressors organized by source type

Note that all stressors are included from each source, even if they are redundant with other sources.

Appendix B-1

Stressors identified in NAVSEA, SSN 774 Class Guard Book Distressed Submarine Survival Guide Forward Escape Trunk (Lockout Trunk), 2013

Identified Stressor	Source
Ammonia gas	Card 11A, Card 11B
Buildup of sanitary waste	Appendix A-1 Sheet 3
Caffeine withdrawal	Appendix A-1 Sheet 2
Carbon monoxide gas	Card 11A, Card 11B
Chlorine gas	Card 11A; Card 6L
Dead bodies/dismemberments	Appendix A-1 Sheet 3
Decreased oxygen levels	Escape vs. Rescue Flow Chart Card 2A; Card 2B; Card 3A; Card 3D; Card 8A; Card 10G; Card 10H; Card 10E
Decreased compartment temperature	Card 1B; Card 8A; Card 10I
Dehydration	Appendix A-1 Sheet 1
Electrical shock/Flying glass	Card 6G
Fire	Card 6L
Flooding	Card 1B; Card 3A; Card 8A
Food rationing	Card 1B; Appendix A-1 Sheet 1; Appendix A-1 Sheet 2
Heat stress	Card 1B; Appendix A-1 Sheet 1; Appendix A-1 Sheet 2; Appendix A-1 Sheet 3
High-fat diet	Appendix A-1 Sheet 1
Hunger	Appendix A-1 Sheet 1
Hydrogen chloride gas	Card 11A, Card 11B
Hydrogen cyanide gas	Card 11A, Card 11B
Illness	Appendix A-1 Sheet 3
Increased carbon dioxide levels	Escape vs. Rescue Flow Chart Card 2A, Card 2B; Card 3A; Card 3C; Card 8A; Card 10B; Card 10G
Increased compartment pressure	Card 1A;Card 1B; Escape vs. Rescue Flow Chart Card 2A; Card 2B; Card 3A; Card 8A; card 10A; Card 10G; Card 10H; Card 10F
Increased compartment temperature	Card 10I; Appendix A-1 Sheet 3
Increased humidity	Card 1B; Card 8A; Card 10I
Lack of potable water	Card 1B; Appendix A-1 Sheet 2
Lithium hydroxide dust	Card 1B; Card 10I; Card 2B; Card 3A; Card 3C; Card 10B; Card 10G
Loss of power	Appendix A-1 Sheet 1; Appendix A-1 Sheet 4; Card 7A; Card 10G
Limited physical activity	Card 1B; Card 10E
Nitrogen dioxide gas	Card 11A, Card 11B

Personal injury	Card 1B; Card 5A; Card 6G
Poor hygiene	Appendix A-1 Sheet 4
Radiation exposure	Escape vs. Rescue Flow Chart Card 2A, Card 2B
Reduced lighting	Card 1B; Appendix A-1 Sheet 4
Sulfur dioxide gas	Card 11A, Card 11B
Tapping on the hull	Card 7A
Toxic gases	Escape vs. Rescue Flow Chart Card 2A; Card 8A
Water rationing	Card 1B; Appendix A-1 Sheet 1; Appendix A-1 Sheet 2

Appendix B-2

Stressors identified in Nuclear Powered Submarine Atmosphere Control Manual (S9510-AB-ATM-010), 2013

Identified Stressor	Source
Ammonia gas	Chapter 11
Increased carbon dioxide levels	Chapter 11
Carbon monoxide gas	Chapter 11
Change in diet	Chapter 11
Chlorine gas	Chapter 11
Decreased oxygen levels	Chapter 11
Dehydration	Chapter 11
Fire	Chapter 11
Flooding	Chapter 11
Heat stress	Chapter 11
Hydrogen chloride gas	Chapter 11
Hyperthermia	Chapter 11
Hypothermia	Chapter 11
Hypoxia	Chapter 11
Increased compartment pressure	Chapter 11
Increased compartment temperature	Chapter 11
Increased humidity	Chapter 11
Lack of potable water	Chapter 11
Life-or-death scenario	Chapter 11
Lithium hydroxide dust	Chapter 11
Loss of power	Chapter 11
Nitrogen dioxide gas	Chapter 11
Personal injury	Chapter 11

Appendix B-3

Stressors identified in Review of Submarine Escape Action Levels for Selected Chemicals, 2002

Identified Stressor	Source
Ammonia gas	Chapter 2
Carbon monoxide gas	Chapter 3
Chlorine gas	Chapter 4

Hydrogen chloride gas	Chapter 5
Hydrogen cyanide gas	Chapter 6
Hydrogen sulfide gas	Chapter 7
Nitrogen dioxide gas	Chapter 8
Sulfur dioxide gas	Chapter 9

Appendix B-4

Stressors identified in NATO Policy Documents

Identified Stressor	Source
Buildup of sanitary waste	NATO (2014, 2017)
Carbon monoxide gas	NATO (2014, 2017)
Chlorine gas	NATO (2014, 2017)
Cold-exposure (water)	NATO (2014)
Decreased compartment temperature	NATO (2014, 2017)
Decreased oxygen levels	NATO (2014, 2017)
Limited physical activity	NATO (2017)
Dehydration	NATO (2014, 2017)
Fire	NATO (2014, 2017)
Flooding	NATO (2017)
Food rationing	NATO (2014, 2017)
Heat exhaustion	NATO (2017)
Heat stress	NATO (2017)
Heat stroke	NATO (2017)
Hyperthermia	NATO (2014, 2017)
Hypothermia	NATO (2014, 2017)
Hypoxia	NATO (2014)
Increased carbon dioxide levels	NATO (2014, 2017)
Increased carbon dioxide partial pressure	NATO (2014)
Increased compartment pressure	NATO (2014, 2017)
Increased compartment temperature	NATO (2014, 2017)
Increased oxygen partial pressure	NATO (2014)
Injury	NATO (2017)
Isolation	NATO (2017)
Lack of communication with rescue forces	NATO (2017)
Limited physical activity	NATO (2014)
Oxygen toxicity	NATO (2014)
Psychological stress	NATO (2017)

Appendix B-5

Stressors identified in Other Policy Documents

Identified Stressor	Source
Blunt trauma	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Penetrating trauma	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Thermal injury	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Pulmonary injury	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Wounds	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)

Death	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Unhealthy atmosphere	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Hypothermia	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Hyperthermia	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Increased compartment pressure	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Exhaustion	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Toxic gas	ANNEX Q to COMSUBLANT/COMSUBPAC (2010)
Decreased oxygen levels	Advanced Undersea Systems Program Manager (PMS 394) (2010)
Increased carbon dioxide levels	Advanced Undersea Systems Program Manager (PMS 394) (2010)
Loss of power	Advanced Undersea Systems Program Manager (PMS 394) (2010)

Appendix B-6

Stressors identified in NSMRL Technical Reports

Identified Stressor	Source
Boredom	Horn et al. (2009)
Buildup of sanitary waste	Horn et al. (2009)
Caffeine withdrawal	Horn et al. (2009)
Carbon monoxide gas	Alvis (1952); *International workshop on escape and survival from submersibles* 1974)
Chlorine gas	Alvis (1952)
Confinement	Gertner, Duplessis, and Horn (2008); *International workshop on escape and survival from submersibles* 1974)
Decreased oxygen levels	Francis et al. (2002); Horn et al. (2009)
Decreased compartment temperature	Francis et al. (2002); Kargher et al. (2001)
Fatigue	Horn et al. (2009)
Fire	Alvis (1952); *International workshop on escape and survival from submersibles* 1974); Kargher et al. (2001); Latson (1999); Quatroche and Horn (2007); Yarnall, Horn, and Hughes (2009)
Flooding	Eckenhoff (1984); Kargher et al. (2001); Quatroche and Horn (2007); Yarnall et al. (2009)
Food rationing	Francis et al. (2002); Horn (2009); Horn et al. (2009)
Headaches	DeMers, Horn, and Hughes (2009); Horn et al. (2009)
Heat stress	Horn (2009); Horn et al. (2009)
High-fat diet	Horn et al. (2009)
Increased carbon dioxide levels	Alvis (1952); Francis et al. (2002); Gertner et al. (2008); Horn et al. (2009); *International workshop on escape and survival from submersibles* 1974); (Vanderweele, Hughes, & Horn, 2007)
Increased carbon dioxide partial pressure	Alvis (1952)
Increased compartment pressure	Alvis (1952); Eckenhoff (1984); Horn et al. (2009);

	Horn, Reed, Quatroche, and Wagner (2008); *International workshop on escape and survival from submersibles* 1974); Kargher et al. (2001); Quatroche and Horn (2007)
Increased humidity	Francis et al. (2002); Horn (2009); Horn et al. (2009); Kargher et al. (2001); (Vanderweele et al., 2007)
Increased oxygen partial pressure	Alvis (1952)
Increased compartment temperature	Horn (2009)
Injury	Horn et al. (2009); Horn et al. (2008); *International workshop on escape and survival from submersibles* 1974); Yarnall et al. (2009)
Lack of potable water	Horn (2009); Horn et al. (2009)
Life-or-death scenario	Gertner et al. (2008); Horn et al. (2008); *International workshop on escape and survival from submersibles* 1974); Quatroche and Horn (2007)
Limited physical activity	Francis et al. (2002); Horn et al. (2009)
Lithium hydroxide dust	Francis et al. (2002); Horn et al. (2009); (Vanderweele et al., 2007)
Loss of power/minimal power	Quatroche and Horn (2007)
Nitrogen narcosis	*International workshop on escape and survival from submersibles* 1974)
Oxygen toxicity	Alvis (1952); *International workshop on escape and survival from submersibles* 1974)
Panic	*International workshop on escape and survival from submersibles* 1974)
Radiation exposure	Francis et al. (2002); Kargher et al. (2001); Quatroche and Horn (2007); Yarnall et al. (2009)
Reduced lighting	Gertner et al. (2008); Horn et al. (2009); Yarnall et al. (2009)
Seeing dead crew members	Gertner et al. (2008); Horn et al. (2008)
Tapping on the hull	Horn, Keller, Reini, Vanderweele, and Quatroche (2010)
Toxic gases	Francis et al. (2002); Horn et al. (2010); *International workshop on escape and survival from submersibles* 1974); Kargher et al. (2001); Yarnall et al. (2009)
Water rationing	Horn (2009); Horn et al. (2009)
Water sprays	Kargher et al. (2001)

Appendix B-7

Stressors identified in Narration of Events (B.A.P Pacocha (SS-48)), 1989

Identified Stressors	Source
Chlorine gas	Harvey and Carson (1989)
Dead bodies/dismemberments	Harvey and Carson (1989)
Decreased oxygen levels	Harvey and Carson (1989)
Fire	Harvey and Carson (1989)
Flooding	Harvey and Carson (1989)
Food rationing	Harvey and Carson (1989)

Increased carbon dioxide levels	Harvey and Carson (1989)
Increased compartment temperature	Harvey and Carson (1989)
Injury	Harvey and Carson (1989)
Lack of potable water	Harvey and Carson (1989)
Limited physical activity	Harvey and Carson (1989)
Reduced lighting	Harvey and Carson (1989)
Toxic gases	Harvey and Carson (1989)

Appendix B-8

Stressors identified in Submarine Casualties Booklet, 1966

Identified Stressors	Source
Air contaminants	COCHINO (1949); HMS THETIS (1939); USS TANG (1944)
Chlorine gas	S-5 (1921); DUKKEREN (1916); UB-57 (1918); USS SQUALUS (1939); UMPIRE (1941); X-3 (1942); WELIMAN X (--);U-741 (--); STRATAGEM (1944); U-1195 (1945)
Cold-exposure (water)	X-3 (1942), USS Squalus (1939)
Confinement/isolation	S-4 (1927); O-9 (1941); U-3 (DATE); DYKKEREN (1916); E-41 (1916); U-51 (1916); UB-57 (1918); Poseidon (1931); USS SQUALUS (1939); HMS THETIS (1939); U-40 (1939); U-64 (1940); UMPIRE (1941); P-32 (1941); X-3 (1942); U-741 (--); U-1195 (1945); USS TANG (1944)
Decreased compartment temperature	USS SQUALUS (1939)
Decreased oxygen levels	X-3 (1942); WELIMAN X (--);U-741 (--);U-1195 (1945); USS TANG (1944)
Electrical shock	E-41 (1916)
Fear	X-3 (1942)
Fire	COCHINO (1949); HMS THETIS (1939); USS TANG (1944)
Flooding	S-5 (1921); R-6 (1921); S-48 (1921); S-51 (1923) S-51 (1925); S-4 (1927); USS SQUALUS (1939); R-12 (1943); COCHINO (1949); DYKKEREN (1916); E-41 (1916); U-51 (1916); K-13 (1917); UB-57 (1918); POSEIDON (1931); USS SQUALUS (1939); HMS THETIS (1939); U-40 (1939); U-64 (1940); UMPIRE (1941); P-32 (1941); PERSEUS (1941); X-3 (1942); UNTAMED (1943); WELIMAN X (--); U-533 (1943); U-741 (--); STRATAGEM (1944); U-1199 (--);U-1195 (1945); USS TANG (1944)
Headaches	HMS THETIS (1939)
Increased carbon dioxide levels	USS SQUALUS (1939); HMS THETIS (1939);

	UNTAMED (1943); U-741 (--);U-1195 (1945)
Increased carbon dioxide partial pressure	U-741 (--)
Increased compartment pressure	DYKKEREN (1916); E-41 (1916); UB-57 (1918); HMS THETIS (1939); POSEIDON (1931); UMPIRE (1941); P-32 (1941); PERSEUS (1941); U-533 (1943); U-741 (--);STRATAGEM (1944); U-1199 (--); U-399 (1945); XE-11 (1945); U-1195 (1945); USS TANG (1944); USS TANG (1944)
Increased oxygen partial pressure	U-741 (--); U-1199 (--)
Injury	COCHINO (1949); E-41 (1916); PERSEUS (1941); UMPIRE (1941); USS TANG (1944)
Life-or-death scenario	R-6 (1921); S-51 (1925); S-4 (1927); USS SQUALUS (1939); S-26 (1942); R-12 (1943); COCHINO (1949); DYKKEREN (1916); E-41 (1916); U-51 (1916); K-13 (1917); UB-57 (1918); POSEIDON (1931); HMS THETIS (1939); U-40 (1939); H-49 (1940); UMPIRE (1941); P-32 (1941); PERSEUS (1941); UNTAMED (1943); U-741 (--); STRATAGEM (1944); U-1199 (--); U-1195 (1945); USS TANG (1944)
Loss of confidence	HMS THETIS (1939)
Loss of power	COCHINO (1949)
Pain	STRATAGEM (1944)
Panic	STRATAGEM (1944)
Reduced lighting	E-41 (1916); U-40 (1939); P-32 (1941); PERSEUS (1941); U-533 (1943); STRATAGEM (1944); USS TANG (1944)
Seeing dead crew members	PERSEUS (1941)
Toxic gases	E-41 (1916); U-51 (1916)
Unhealthy atmosphere	K-13 (1917); UNTAMED (1943)

Appendix B-9

Stressors identified in UMO Theses

Identified Stressor	Source
Air contaminants	Eckenhoff (1980)
Carbon monoxide gas	Eckenhoff (1980); Latson (1999); Mole (1989)
Chlorine gas	Eckenhoff (1980); Mole (1989); Neuman (1974)
Cold-exposure (water)	Neuman (1974)
Decreased compartment temperature	Eckenhoff (1980)
Decreased oxygen levels	Eckenhoff (1980); Mole (1989)
Dehydration	Ochsner (2003)
Electrical shock	Neuman (1974)
Fatigue	Ochsner (2003)
Fire	Eckenhoff (1980); Mole (1989)

Flooding	DeMers and Lehnhardt (2005); Eckenhoff (1980); Mole (1989); Neuman (1974); Rentsch (1956)
Food rationing	Mole (1989)
Heat exhaustion	Ochsner (2003)
Heat stroke	Ochsner (2003)
Hypothermia	Manalaysay and Cassano (1984); Mole (1989)
Hypoxia	Mole (1989)
Increased carbon dioxide levels	(Eckenhoff, 1980; McMillan, 1970; Mole, 1989; Neuman, 1974)
Increased carbon dioxide partial pressure	Mole (1989)
Increased compartment pressure	DeMers and Lehnhardt (2005); Eckenhoff (1980); Latson (1999); Maurer (1999); McMillan (1970); Mecklenburg (2001); Rentsch (1956)
Increased nitrogen partial pressure	DeMers and Lehnhardt (2005); Eckenhoff (1980); McMillan (1970); (Mole, 1989); Neuman (1974)
Increased oxygen partial pressure	DeMers and Lehnhardt (2005); Eckenhoff (1980); Maurer (1999); Mole (1989)
Thermal injury	Latson (1999)
Injury	Latson (1999); McMillan (1970); Neuman (1974)
Lack of potable water	Ochsner (2003)
Limited physical activity	Ochsner (2003)
Smoke inhalation	Latson (1999)
Loss of power	Eckenhoff (1980); Ochsner (2003)
Nitrogen narcosis	McMillan (1970)
Oxygen toxicity	Eckenhoff (1980); Maurer (1999); McMillan (1970); Neuman (1974)
Musculoskeletal trauma	Latson (1999)
Panic	McMillan (1970)
Psychological stress	Mole (1989)
Stress	McMillan (1970); Ochsner (2003)
Toxic gases	McMillan (1970)
Water rationing	Mole (1989)

Appendix B-10

Stressors identified by Subject Matter Experts (SMEs)

Identified Stressor	Source
Change in diet	HMCS (SS/FMF) Mark Jarvis
Change in leadership	CDR Anthony Quatroche, USN (Ret.)
Drowning	CDR Anthony Quatroche, USN (Ret.)
Ear/sinus pain	SurgCDR Lesley Whybourn, RN
Feeling of impending doom	HMCS (SS/FMF) Mark Jarvis
Interpersonal conflict	HMCS (SS/FMF) Mark Jarvis; SurgCDR Lesley Whybourn, RN
Insufficient training	CDR Anthony Quatroche, USN (Ret.);

	SurgCDR Lesley Whybourn, RN
Lack of control	SurgCDR Lesley Whybourn, RN
Red emergency lighting	CDR Anthony Quatroche, USN (Ret.)
Resignation	SurgCDR Lesley Whybourn, RN
Wet clothing/bedding	SurgCDR Lesley Whybourn, RN

Appendix C: U. S. Navy's Proposed Submarine Escape Action Levels (SEALs; 1998) adapted from Review of Submarine Escape Action Levels for Selected Chemicals (2002, p. 289)

	Navy's Proposed SEALs (ppm)	
Gas	SEAL 1	SEAL 2
Ammonia	75	125
Carbon monoxide	125	150
Chlorine	1	2.5
Hydrogen chloride	20	35
Hydrogen cyanide	10	15
Hydrogen sulfide	10*	20*
Nitrogen dioxide	0.5	1
Sulfur dioxide	20	30

If SEAL 1 is exceeded, then survivors are to wait 24 hours before donning EABs. If air pollutant concentration is ≥ SEAL 2, with depth of the submarine being at a depth < 600 ft, survivors are advised to escape; if depth is > 600 ft., survivors are advised to immediately don EABs and await rescue (NAVSEA, 2013c).

* These SEAL levels have been proposed but have not been implemented in current DISSUB guard books.